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Defects and Impurities in 4H- and 6H-SiC Homoepitaxial Layers: Identification, Origin, Effect on Properties of Ohmic Contacts and Insulating Layers and Reduction

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A hot wall chemical vapor deposition system has been constructed to deposit thin films of 4H- and 6H-SiC and AlN. The design incorporates a separate load lock from which the growth chamber and a RHEED chamber are attached. Operation awaits the completion of the laboratory upfitting to address the safety requirements necessary to use silane. Characteristics of high voltage, planar, PN junction diodes fabricated on 4H-SiC using field plate as an edge termination are reported for the first time. The diodes were formed by nitrogen implantation into p-type epitaxial layers and aluminum implantation into n-type epitaxial layers at 1000°C, using a deposited and patterned SiO_2 layer as the mask.

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I. Introduction

The two most important materials-related problems affecting the performance of all SiC devices and their associated components (e.g., contacts) are the defects and the undesired impurities which become incorporated in the homoepitaxial SiC layers in which all devices are currently fabricated. Bhatnagar [1] has shown that the reverse blocking leakage current in high voltage Schottky diodes is three orders of magnitude higher than theoretically predicted as a result of defects in the epi-layer. The formation of micropipes, stepped screw dislocations, interacting dislocation loops, polyganized networks of dislocations and growth twins as well as stacking faults during the sublimation growth of SiC boules are likely the root cause of some of the defects in the epitaxial layer. However, with the exception of the micropipes, the types and concentrations of line, planar and other three-dimensional defects and their effect on the performance of devices and individual device components in the important epi-layer have not been similarly determined. As such, it is not known which of the latter defects actually are translated from the wafer into the epi-layer during its deposition and, therefore, should be vigorously controlled during boule growth and which defects are generated during deposition.

The relatively uncontrolled occurrence of the n-type donor of N and deep level compensating impurities such as Ti in the epilayer have been identified via secondary ion mass spectrometry, photoluminescence and cathodoluminescence investigations. However, the origins of essentially all of these impurities are unknown. For high-temperature, -power and -frequency devices, it is highly desirable to control or eliminate these impurities such as to attain undoped films with uncompensated carrier concentrations of 10^{14} cm^{-3}—two orders of magnitude lower than what is, at present, normally achieved in standard commercial depositions.

The formation of low resistivity and thermally stable ohmic contacts to 4H- and 6H-SiC remains a serious problem in the development of SiC device technology. For SiC power devices to have an advantage over Si, the contact resistivities must be below 1×10^{-5} W-cm^2, as noted by Alok, *et al.* [2]. In addition, the electrical characterization of state-of-the-art SiC films depends on the ability to fabricate ohmic contacts on material with low carrier concentrations. Therefore, better ohmic contacts are needed both for improving device performance and for improving the quality of films which can be grown. The thermal stability of ohmic contacts is of particular concern for p-type SiC, which have traditionally relied on low melting point Al or Al alloys to dope the SiC surface below the contacts. These materials are not suitable for devices intended for high-temperature operation. While the fabrication of ohmic contacts to SiC has also normally depended on the attainment of a very heavily-doped near-surface region, the introduction during deposition of high levels of dopants in the near surface device region of the epi-layer prior to the deposition of the contact or by ion implantation through the contact makes probable the introduction of point and line defects as a result of the induced strain in the lattice.

Based on all of these issues and recent experiments already performed at NCSU, our goals are to produce contacts which are thermally stable and have low contact resistivities while also reducing the need for doping by ion implantation.

To fabricate most microelectronic devices, the growth or deposition of stable insulators is needed to provide both passivating layers and gate dielectrics. Silicon carbide is almost invariably thermally oxidized, albeit at a slower rate, in the same manner and temperature range that is employed for Si. Most of the previous studies regarding the oxidation of SiC have been concerned with polycrystalline materials. It has been shown by Harris and Call [3] and Suzuki, *et al.* [4] that the (0001) face of 6H-SiC oxidizes according to the same linear-parabolic equation reported for Si by Deal and Grove [5]. The model states that the initial stage of oxidation is reaction rate limited and linear, but becomes parabolic as the diffusion of the oxidant through the oxide becomes the rate limiting factor. Research at NCSU by Palmour, *et al.* [6] has demonstrated that the oxidation process on SiC in wet and dry oxygen and wet argon obeys the linear-parabolic law. Both wet processes had a slower rate than dry oxidation at 1050°C and below. The dry oxides exhibited a very flat surface; in contrast, SEM and TEM revealed that wet oxidation preferentially oxidizes dislocation bands, causing raised lines on the oxide and corresponding grooves in the SiC. It was proposed that the much higher solubility of H_2O in SiO_2 as compared to that of O_2 allows wet oxidation to be preferential.

All of the oxidation studies on all polytypes of semiconductor quality SiC have been conducted on n-type material with the exception of the investigation by Palmour *et al.* [6]. The objective of this study was the determination of the redistribution of the common electrical dopants of N, P, Al and B during thermal oxidation of SiC films at 1200°C in dry O_2. Experimental segregation coefficients and interfacial concentration ratios were determined. Secondary ion mass spectrometry revealed that B and Al depleted from the SiC into the growing oxide while N and P were found to pile up in the SiC as a result of the loss of the SiC to the oxide formation. Aluminum is now used almost universally as the p-type dopant in SiC. The electrical properties of oxides thermally grown on n-type SiC normally have reasonably favorable characteristics of high breakdown voltage and low leakage currents. However, the reverse is true for thermally grown oxides on p-type SiC, as shown by Baliga and his students at NCSU. It is believed that at least two of the causes of the poor performance on a p-type material are the existence of the Al in the oxide and at the oxide/SiC interface and the dangling oxygen bonds which this species creates in the oxide as a result of a difference in oxidation state (+3) compared to that of Si (+4) and the existence of C at the SiC/insulator interface. Methods of effectively cleaning SiC surfaces prior to oxidation to deposit and grow oxides on p-type material under UHV conditions and determine the effect of Al redistribution and C concentrations at the interface on the properties of the oxide must be determined. In addition,

the effect of existing line and planar defects in the SiC epi-layer on the properties of the thermally grown and deposited oxide must be ascertained.

The research conducted in this reporting period and described in the following sections has been concerned with the (1) design and construction of a new hot wall CVD SiC system for the deposition and doping of 6H- and 4H-SiC and AlN films, and (2) characteristics of high voltage, planar, PN junction diodes fabricated on 4H-SiC using field plate as an edge termination and reported for the first time. The following individual sections detail the procedures, results, discussions of these results, conclusions and plans for future research. Each subsection is self-contained with its own figures, tables and references.

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II. Growth Via Hot Wall Chemical Vapor Deposition and Characterization of 6H- and 4H-SiC Thin Films

A. Introduction

A silicon carbide system is being built in order to grow silicon carbide thin films of high quality. A design has been developed. Most parts have been received and have been assembled.

B. Experimental Procedure

The system design is comprised of a six-way cross, serving as a loadlock, from which two separate chambers are attached. A high-temperature growth chamber and RHEED analysis chamber are attached on each side perpendicular to the axis of the loadlock. The latter chamber will be used to monitor film crystallinity, crystal structure and the formation of new surfaces. The sample will be transferred to and from the various chambers on a SiC-coated graphite susceptor platform on which the sample will be placed. The transfer mechanism consists of a platform which is moved from chamber to chamber by means of a manipulator rod which is fastened to the side of the susceptor.

The growth chamber consists of a rotating module, to which the susceptor is attached. Growth will occur on the sample in an upside-down position, with gases flowing upward, while the susceptor is being rotated. The susceptor is attached to the rotating rod assembly by a groove into which the susceptor slides when transfer of the sample takes place. Once the sample is transferred to the rotating rod, the rod is brought down to the quartz portion of the reaction chamber. Here, the sample is heated via RF coil, and gases are introduced from the bottom of the reactor. A design which incorporates a graphite cylinder for hot wall CVD growth is in progress. The growth temperature will be monitored by means of a standing pyrometer mounted outside the quartz chamber and aimed at the sample. Growth processes parameters, such as gas flow rate and pressure, will be monitored by electronic components. Gas flow will be controlled by mass flow controllers and pressure by capacitance manometers.

The RHEED (reflection high-energy electron diffraction) chamber, attached on another side of the loadlock chamber, will be attached to monitor film crystallinity, crystal structure and the formation of new surfaces. Because attempts to grow high-quality crystalline SiC films, a RHEED chamber attached to a nominal high vacuum to prevent direct exposure to atmosphere after growth will be useful to characterize the film.

The SiC growth process will consist of introducing SiH_4 and C_2H_4 as the reactive components in a H_2 carrier. Nominal flow values will be on the order of 1 to 10 sccm for each. Hydrogen carrier flow rates will be on the order of three liters per minute. Other reactant sources which will be attached to the system include NH_3 and an N_2/H_2 mixture for n-type doping and triethlyaluminum for and p-type doping.

C. Accomplishments to Date

- A design has been developed for sample transfer, growth, and RHEED analysis.
- A support frame to provide physical support to the system has been designed and built.
- Three six-way crosses have been put together with the adjoining gate valves on the frame, and available flanges and window ports have been attached.
- A quartz chamber-to-cross assembly has been machined, which will provide a sealed interface between two parts of the growth chamber.
- Quartz cylinders have been cut to design dimensions.
- Flange parts, pressure gauge attachments, pump connection parts, and a rotating rod assembly, have been machined.
- An RF generator has been refurbished and delivered back to us, to be used to provide RF heating to the susceptor.
- Assembly of a switch panel to control the nupro valves and to enable computer control.
- A RHEED chamber manipulator has been fitted with a holder which will accommodate the susceptor upon transfer.
- Electrical wiring of the switch panel to control the nupro valves has been assembled.
- Various gas lines on a panel to be mounted on one side of the system has been put together.
- Installation of electrical and water utilities for the system, as well as safety changes in the laboratory have largely been completed.
- A gas monitoring system is being installed for safe system operation.

D. Discussion

The proposed design was developed with many sources of input. A number of constraints determined the design configuration and materials used in the system.

One of the main concerns was the high operating temperature of the growth chamber. Since temperatures around 1600-1700°C were going to be used to grow SiC thin films, it was determined that quartz would be the best material for the growth portion of the chamber. Once this was determined, a design had to be developed to cool the chamber. A double-walled quartz vessel, water cooled around the perimeter, was determined to be the optimum mode of cooling. A hot wall CVD system was determined to be the best method for achieving a high growth rate. Discussions are underway at this time to design the most appropriate graphite inner chamber inside the quartz cylinders for this purpose.

Another concern was the transfer mechanism of the susceptor and the placement of samples on the susceptor surface. It was decided that small silicon carbide screws would be the most flexible for our purposes to accommodate various sized samples. For the transfer mechanism, a

simple tongue-in-groove assembly, moved between chambers by means of a transfer arm which would screw into the side of the susceptor, was deemed simplest and most practical.

E. Conclusions/Future Research Plans and Goals

A system design for the deposition of SiC thin films has been developed. Most components have been designed or received. A graphite inner chamber has been made to accommodate hot wall CVD growth. The purge panels assembly, RF coil assembly, and final gas line connections are being performed. A representative from Tocco will insure proper start up of the system. Leak checking, followed by an initial test of the growth conditions, will follow.

III. High Voltage, Planar, Field Plate Edge Terminated 4H-SiC PN Junction Diodes

ABSTRACT

The characteristics of high voltage, planar, PN junction diodes fabricated on 4H-SiC using field plate as an edge termination are reported for the first time. The diodes were formed by nitrogen implantation into p-type epitaxial layers and aluminum implantation into n-type epitaxial layers at 1000 °C, using a deposited and patterned SiO_2 layer as the mask. Post implantation anneals were performed at 1300 °C and 1400 °C for the nitrogen and aluminum implanted samples, respectively. The nitrogen implanted diodes with field plate exhibited a breakdown voltage of 1100 V, which is nearly 70 % of the theoretical breakdown voltage. The average reverse leakage currents of these diodes were as low as $1x10^{-5}$ A/cm^2 just before breakdown. The aluminum implanted diodes without a field plate also supported high voltages upto 800 V. While the field plate improved the reverse characteristics of the nitrogen implanted diodes, it was found to deteriorate those of the aluminum implanted diodes.

INTRODUCTION

Ion Implanted planar p-n junctions are useful for fabrication of silicon carbide discrete devices and integrated circuits. PN junctions are the starting point in the development of any semiconductor technology and they are vital components in many SiC power devices like MOSFETS, JFETS[1] and ACCUFETS[2]. PN junctions in SiC have been formed either using multiple epitaxial layers or unmasked ion implantation in the past[3-6]. This approach does not offer planar selective area doping which is desirable for making SiC power devices. Moreover, a planar junction is preferred due to difficulty in passivation of mesa-etched surfaces. As opposed to Si technology, thermal diffusion cannot be used due to the extremely low diffusion coefficients of dopants at temperatures where dielectric masking layers can be used for selective area doping. Hence, in order to improve the commercial viability of SiC devices, the successful development of planar, high voltage, ion implanted PN junction technology is essential.

Most of the ion implantation studies in the past have been on 6H- SiC[4-9]. High voltage planar diodes on 6H SiC, using SiO_2 as the mask, were demonstrated for the first time using nitrogen and boron implants[10,11]. Further, various planar edge terminations such as floating metal rings and resistive Schottky barrier field plates have been explored for 6H-SiC devices [12] but only 50% of ideal breakdown voltage was achieved. A planar, near ideal, edge termination using Argon implantation [13,14] has been reported for 6H in Proc. 5th International Symposium on Power Semiconductor Devices and ICs SiC Schottky barrier diodes but the leakage current is greatly increased by the implanted region. This method was also demonstrated for 4H SiC with breakdown voltages exceeding those reported for 4H SiC mesa edge terminated diodes[15]. Most recently, a 3.4 kV ion implanted PIN-rectifier has been implemented in 4H-SiC with low leakage currents obtained by using junction termination extension created by boron ion

implantation[16]. In this paper, the characteristics of high voltage, planar PN junctions, formed by ion implantation through an oxide into 4H SiC epitaxial layers, with field plate edge termination, are reported for the first time.

DEVICE FABRICATION

In this study, N^+P junction diodes were fabricated by nitrogen implantation into 4H SiC p-type epitaxial layers grown on p+ substrate. Similarly, P^+N junction diodes were fabricated by aluminum implantation into 4H SiC n-type epitaxial layers grown on n+ substrate. The substrate doping and thickness in both cases were $1x10^{18}cm^{-3}$ and 300 μm respectively. The epitaxial layer was 10 μm thick and its doping varied between $8.5x10^{15}cm^{-3}$ and $1x10^{16}cm^{-3}$. Circular diodes of 200 μm diameter were formed by implanting through windows made in 7000 Å thick LPCVD oxide. Dopants were implanted through a 500 Å pad oxide using a multiple implant sequence with energies 25, 50, 75 and 120 keV to give box-profiles with a total dose of $2.6x10^{15}$ cm^{-2} and $6.8x10^{15}$ cm^{-2} in case of nitrogen and aluminum implants, respectively. It has been shown that increased surface dopant concentration leads to reduced ohmic contact resistivity[17], hence a pad oxide was used to ensure that the peak dopant concentration occurs at the surface. Monte Carlo simulations performed using SUPREM showed that these implant conditions would yield a junction depth of 0.25 μm in the case of the nitrogen implant and 0.2 μm in the case of the aluminum implant. All implantations were done at 1000°C because it has been shown that hot implantation is essential to reduce the crystal damage produced during ion implantation and improve activation of the dopants in SiC[7-9]. Post-implantation proximity anneals were done at 1300°C and 1400°C for the nitrogen and aluminum implants, respectively, in argon for 30 minutes. After the anneal, the pad oxide was etched out and aluminum contacts were formed by lift-off to yield structures both with and without field plates. Blanket evaporation of aluminum was done on the back side of the wafer to form ohmic contacts to the substrate. Fig.1 shows the cross-section of the fabricated diodes.

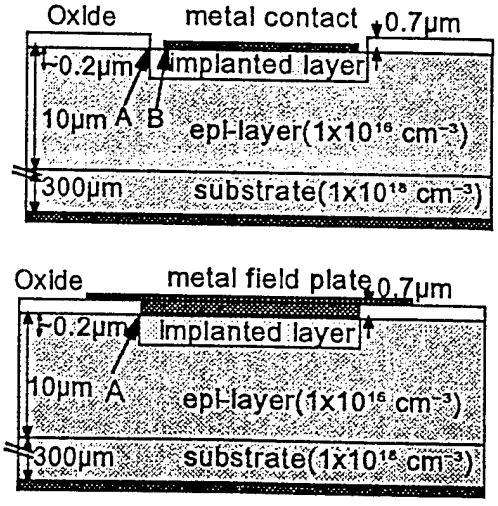

Fig.1. Cross-section of fabricated planar diodes with and without field plate edge termination.

EXPERIMENTAL RESULTS

The reverse I-V characteristics of typical nitrogen implanted diodes on 4H SiC with and without field plates are shown in Fig.2. The N^+P junction diodes without field plates showed good reverse blocking characteristics with a maximum breakdown voltage of 800±40 V and average leakage currents in the range of $1x10^{-4}$ A/cm² prior to breakdown. The N^+P diodes with field plates showed improved reverse characteristics with higher breakdown voltages of 1100± 60V and lower average leakage currents in the range of $1x10^{-5}$ A/cm². The breakdown voltage is nearly 70 % of the theoretical parallel plane ideal breakdown voltage of about 1600 V for a diode with these epitaxial layer specifications. A total of 30 devices were measured, 15 with field plates and 15 without field plates, and it was found that the presence of field plate improved the reverse I-V characteristics of the diodes consistently and as expected from theory[18]. Field plates of length 5, 10, 15 and 20 μm were fabricated and the breakdown voltage was found to be independent of the of field plate length in the above mentioned range The variation in the leakage currents just before breakdown for the N^+P diodes across the sample is shown in Fig.3. The average leakage current for diodes with field plates, reduced by an order of magnitude when compared to that of diodes without field plates, to a value as low as $1x10^{-5}$ A/cm² just before breakdown.

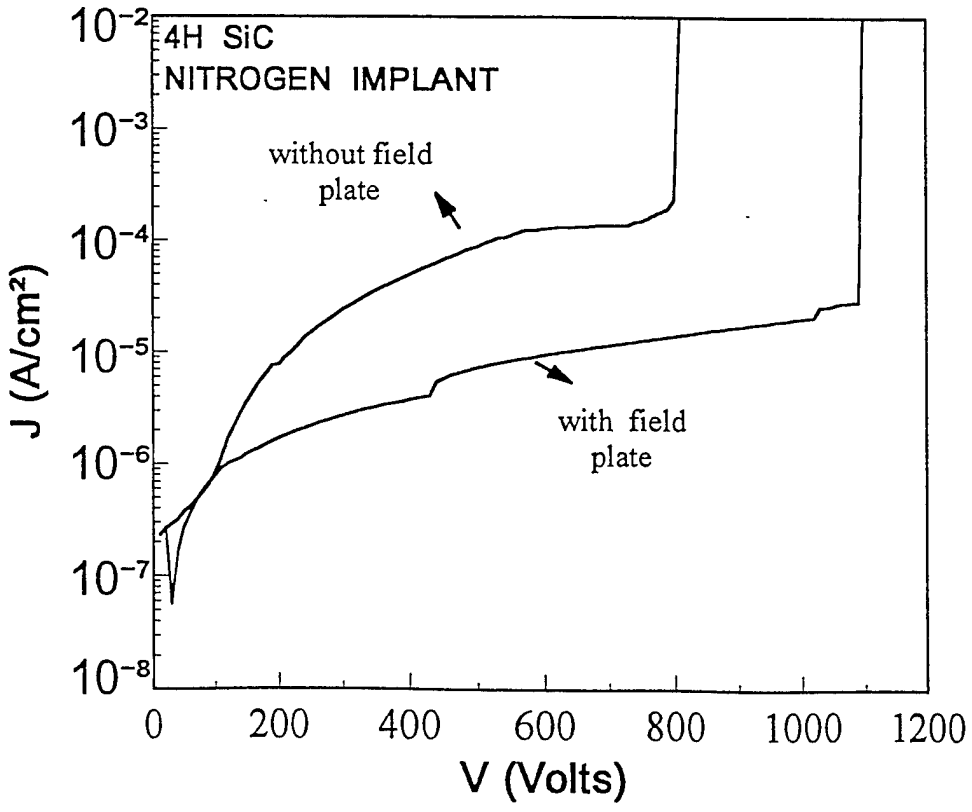

Fig.2. Comparison of reverse I-V characteristics of typical nitrogen implanted diodes on p-type 4H SiC epitaxial layers with and without field plates.

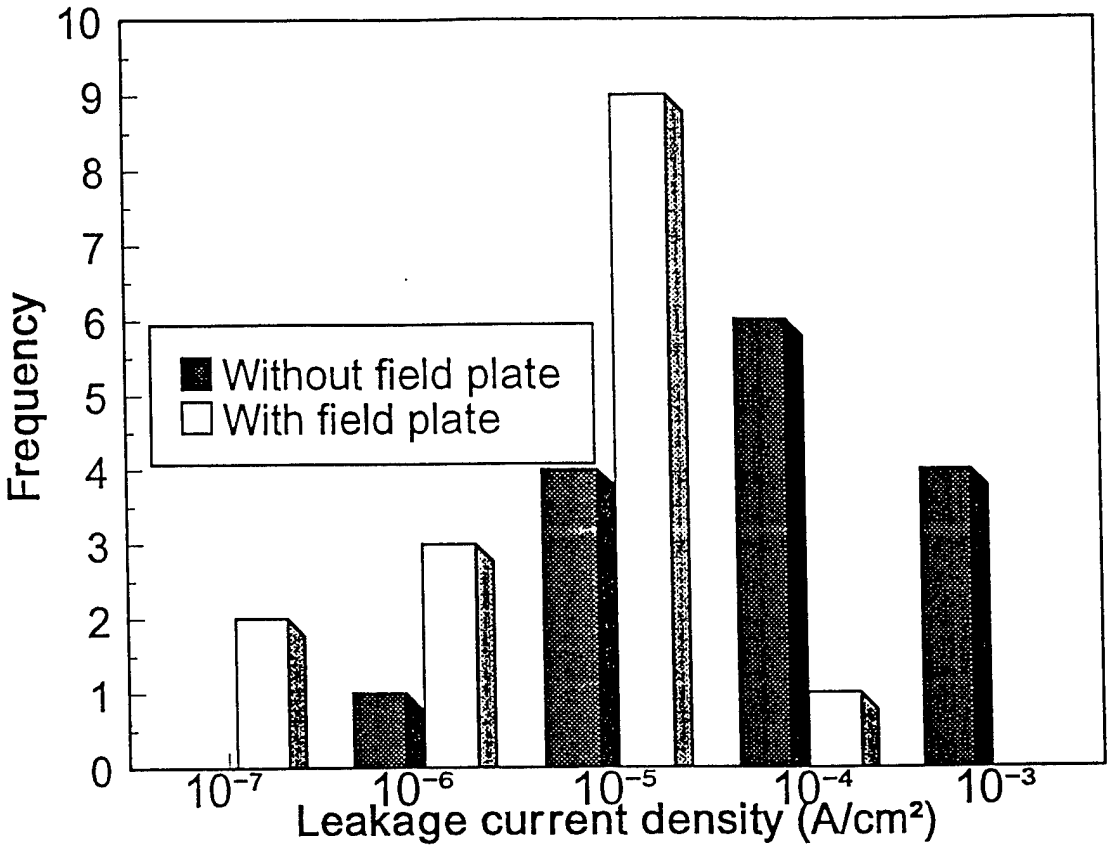

Fig.3. Histogram of reverse leakage current density of nitrogen implanted diodes on 4H SiC just before breakdown.

The aluminum implanted PN junction diodes exhibited higher breakdown voltages without field plates as shown in Fig.4. While the aluminum implanted diodes without field plates showed breakdown voltages of 800±10 V, the ones with field plate supported only 275±40 V. We attribute this to the poor activation of the aluminum implanted region. Aluminum implanted regions are known to suffer poor activation[9], and hence the actual doping in the ion implanted region is much lower than the implanted aluminum concentration. The sheet resistance of the ion implanted region was measured using kelvin test elements on the same wafers, and was found to be 25 kΩ/square which supports the above argument. This results in the presence of a high resistivity layer at the surface near the edges of the diode (between points A and B in Fig.1.) in case of the diodes without field plates. We believe that this region then acts like a junction termination extension and promotes the spreading of the potential along the surface laterally which results in reduced electric field [13-16] at a given voltage for the diodes without field plates. Hence, a higher breakdown voltage is observed for diodes without field plates when compared to diodes with field plates.

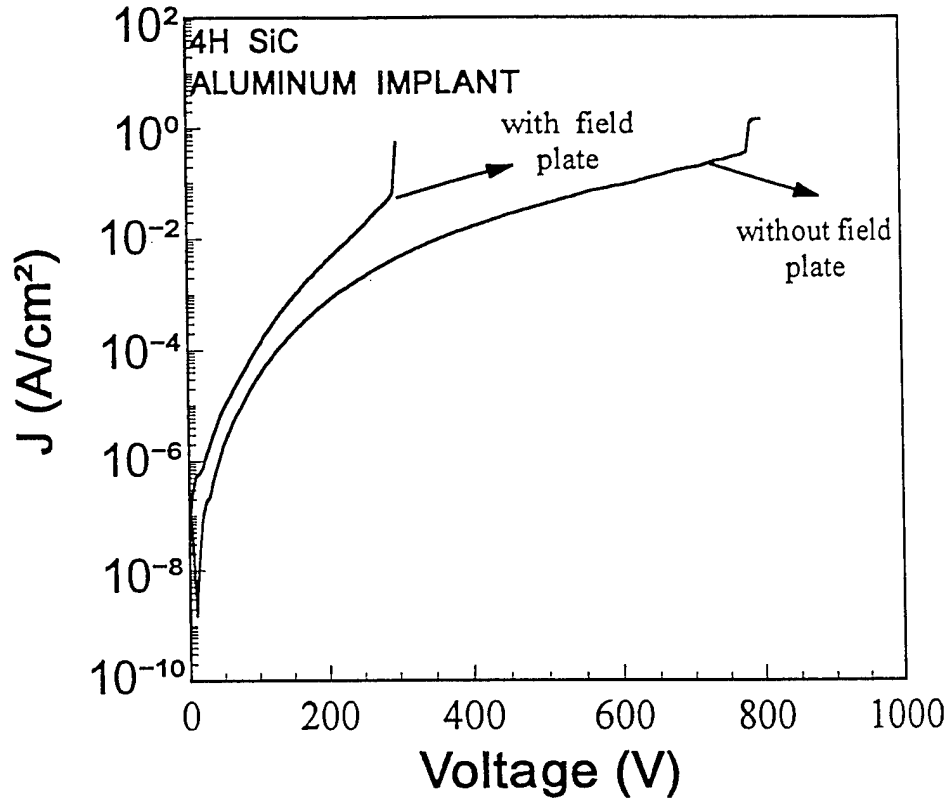

Fig.4. Comparison of reverse I-V characteristics of typical aluminum implanted diodes on n-type 4H SiC epitaxial layers with and without field plates.

CONCLUSIONS

In case of high-voltage devices, edge termination plays an extremely crucial role in determining the breakdown voltage. This paper demonstrates that a simple field plate edge termination can be used to enhance breakdown voltages of planar, nitrogen ion implanted diodes on p-type 4H SiC for the first time. The nitrogen implanted diodes with a field plate edge termination showed breakdown voltages as high as 1100V and average leakage currents as low as $1x10^{-5}$ A/cm². The aluminum implanted diodes without field plates also supported voltages as high as 800 V but with significantly higher leakage currents. While the field plate improved the characteristics of nitrogen implanted diodes, it had a detrimental impact on the aluminum implanted diodes. It is anticipated that the results reported in this paper will be useful for fabrication of both discrete devices and integrated high voltage structures in SiC.

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